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LOW COST SOLAR ARRAY PROJECT:
Composition Measurements by Analytical Photon Catalysis

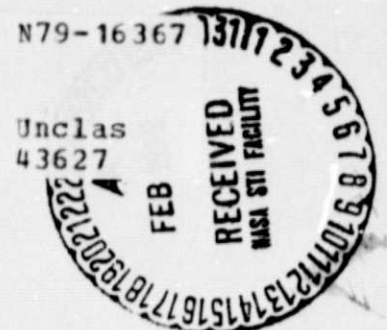
First Quarterly Report

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David G. Sutton, Luis Galvan, James Melzer and Raymond F. Heidner, III

The Ivan A. Getting Laboratories,
The Aerospace Corporation, El Segundo, California 90245

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I. Summary

The object of this research is to assess the applicability of the photon catalysis technique for effecting composition analysis of Silicon samples. In particular, our technique is to be evaluated as a detector for the impurities Al, Cr, Fe, Mn, Ti, V, Mo and Zr. During the first reporting period we have detected Al, Cr, Fe and Mn with the photon catalysis method. We have established the best fluorescence lines to monitor and determined initial sensitivities to each of these elements by atomic absorption calibration. In the course of these tests vapor pressure curves for these four pure substances have also been mapped.

II. Background

Work commenced during the week of September 11 with the assembly of our Analytical Photon Catalysis (MTES)¹ device into a configuration suitable for the study of Silicon impurities. The resulting instrument and its function can best be explained with reference to Figure 1. It consists of a vertical section of quartz tubing 9 cm in diameter. An electrically heated metal vapor furnace is attached to the bottom of the quartz tube, and a 60-l/sec pump, attached at the top of the quartz tube, provides the means to evacuate the system. Argon or Nitrogen injected through the bottom of the furnace assembly entrains the flow of metal atoms from the furnace and carries it into the quartz observation section. In this section, the concentration of Argon is much greater than the metal concentration. A thermocouple placed in contact with the metal in the furnace allows direct measurement of the metal atom source temperature, or an optical pyrometer may be employed by observing the heated metal down through the observation window.

A ring-shaped quartz gas injector is inserted into the apparatus at the junction of the furnace assembly and quartz flow tube. Through this injector, active Nitrogen is introduced into the Ar-metal atom stream. The active Nitrogen, consisting primarily of N atoms, $N_2(A^3\Sigma_u^+)$, and ground-state N_2 , was prepared upstream of the injector by passing N_2 gas through a 70-W microwave discharge. The region of the quartz flow tube approximately 5 cm above the active Nitrogen injector is monitored photoelectrically with an uncooled RCA 1P28 phototube attached to a one meter monochromator. Apart from neutral density filters, which are used at higher metal concentrations to avoid high photomultiplier tube current, no other optics are used. Hollow-cathode lamps can be placed on the opposite side of the flow tube and at the same height as the monochromator entrance slits. They are used as a line source for the atomic absorption measurements to calibrate the fluorescence intensity measurements with respect to metal vapor concentration.

The Ar and N_2 flows are adjusted to give a total pressure of 2-4 Torr. With the microwave generator set to deliver 70 W to the N_2 flow, a pale straw-colored glow is observable downstream of the injector. The furnace is then set to a given temperature, and the resulting atomic line emission intensities are measured.

The most intense and spectroscopically isolated lines are chosen (in accordance with Task 1A of the statement of work) to be the best fluorescence lines to monitor for the purposes of analysis. The intensity is a direct measure of the concentration of the emitting species and can be calibrated as specified in Task 1B at high source temperatures by the atomic absorption technique. If one plots the $\log I$ vs $10^4/T(K)$ a vapor pressure curve results as per Task 1C. These three tasks applied to Al, Cr, Fe and Mn have occupied us for the first quarter.

III. Progress During Reporting Period

When Aluminum is placed in the crucible and heated to 1000° Centigrade the fluorescence spectrum shown in Figure 2 is obtained. All four of the prominent lines are due to the presence of Al vapor in the active Nitrogen stream. The two strongest lines at 309 nm and 396 nm were selected as the best for analysis and their intensities were measured as a function of the source temperature. The results for 309 nm are shown in Figure 3.

The results from two different runs are compared with Hultgren's² recommended vapor pressure curve. The slopes of both our curves are about 20% larger in magnitude than his, but the precision of our measurements is excellent. The most reasonable explanation for this discrepancy is a systematic error in our results due to the use of the pyrometer to measure temperature. We plan to install a digital thermocouple as soon as it is delivered.

The important result is that we have easily measured the Aluminum vapor concentration over more than four orders of magnitude. An attempt to calibrate our signal in order to obtain the absolute concentration of vapor in the observation zone was postponed because of the failure of our aluminum hollow cathode lamp.

In Figures 4 and 5 the MTES spectrum and the vapor pressure curves for Chromium are shown. Cr, like Aluminum, yields a simple line spectrum. The most intense emission lines have wavelengths of 359.4, 357.9 and 425.4 nm. Three additional lines at 360.5, 427.5 and 428.9 nm are also available for monitoring if spectroscopic interferences affect our first choices.

Figure 5 summarizes our temperature dependent measurements at two different wavelengths, 359.4 and 357.9 nm. The slope of the line through our₂ data as determined by least squares fitting agrees within 5% with both Hultgren² and Nesmeyanov.³ Atomic absorption calibration using the 357.9 nm resonance line allows us to put the Cr concentration on an absolute scale as shown on the right side of Figure 5. Using this scale we see₃ that the lowest concentration of Cr detected to date is 1.6×10^7 atoms per cm.³ However, these absolute calibrations cannot be determined with any great confidence, since the experimentally determined oscillator strengths upon which these determinations depend are not known to any great degree of certainty.

As expected when Fe is excited by active Nitrogen a rich atomic emission spectrum results. See Figure 6. The best lines in terms of intensity occur at 344.1,

358.1 and 372.0 nm. Our temperature dependent studies give the vapor pressure curve shown in Figure 7. Our slope is significantly different from Hultgren's recommended curve. Significantly our slope would yield a lower heat of vaporization. If our sample were oxidized a higher value would be expected.

Our results for Manganese are summarized in Figures 8 and 9. The Manganese MTES spectrum is intermediate between Al and Fe in complexity. Fortunately, however, the intensity is concentrated in the triplet features near 280 and 403 nm. Either of these features could be monitored in its entirety with a wide bandpass detector. Maximum sensitivity could probably be achieved in this manner. However, with our monochromator only one line from each triplet could be monitored at a time. Figure 9 shows our system response to the lines at 279.5 nm and 403.1 nm as a function of the reciprocal of the source temperature. These two features are the most intense of their respective groups. Both sets of data give vapor pressure curves whose slopes come within 10% of Hultgren's recommended value when fit with the least squares method to a straight line. The dynamic range of our detector extends over four orders of magnitude.

The data points on Figure 9 that are indicated with a circle were obtained with the atomic absorption technique. This data pegs our MTES measurements on the absolute scale given on the right side of Figure 9 and establishes a sensitivity of less than 10^5 cm⁻¹ for Mn.

IV. Conclusions

Aluminum and Chromium are both sensitively detected by the MTES technique. Their excitation spectra are simple line spectra with most of the fluorescence emanating from a few lines. Both elements give well defined vapor pressure curves with slopes comparable to the published values. This is direct evidence that the intensity of their fluorescence lines is a linear measure of the concentration of these materials in the vapor. The system sensitivity to Aluminum was not directly calibrated, but it can be estimated from rate of vaporization data to be 3×10^5 atoms per cm.³ The sensitivity to Chromium was determined by atomic absorption to be 2×10^5 atoms per cm.³

Iron and Manganese give more complex spectra when excited by contact with active Nitrogen. Each of these elements can be determined analytically by monitoring the most intense spectral features. The sensitivity to Fe can be estimated from rate of vaporization data (Appendix 1) to be 10^7 atoms per cm.³. The atomic absorption method failed for Iron due to a lack of sensitivity of this technique. With Manganese most of the emission intensity is concentrated in six lines and the sensitivity is somewhat higher. As determined by atomic absorption calibration we have detected approximately 5×10^4 atoms per cm.³ of this element.

The results for Tasks IABC are summarized in the following table.

element	<u>Al</u>	<u>Cr</u>	<u>Fe</u>	<u>Mn</u>
best MTES lines (nm)	309.2, 396.1	359.4	344.1	279.5
ancillary lines(nm)	308.2, 394.4	347.9, 425.4	358.1, 372.0	403.1
sensitivity (cm ⁻³)	3×10^5	2×10^5	10^7	5×10^4
ppb	30	20	1000	5

At this point we can speculate about how our quoted sensitivities for these elements will translate into detectivities for impurities in a Silicon matrix. For this purpose one needs to understand that the sensitivities quoted in the table are our detection limits for the elemental vapor in a gas stream. We have also determined that our system saturates when the total metal vapor concentration in the active nitrogen stream reaches 10^{13} atoms per cm³. If we evaporate Silicon from a sample into our active Nitrogen stream and the evaporation process is congruent, then the composition of the vapor will be representative of the sample composition. If Silicon saturates our system at 10^{13} atoms per cm³, then the minimum detectable level of impurity in a solid Silicon matrix by our technique is $(S/10^{13}) \times 10^9$ ppb, where S is our quoted sensitivity. Applying this formula to the third row of the above table gives the fourth row. Thus, we can currently expect to ultimately measure from 5 ppb Mn to 1000 ppb Fe in silicon with our technique. However, we expect to improve on this with a combination of improved light collecting efficiency and increased threshold for saturation.

A comparison with our observed MTES lines with the so called persistent lines of the elements is also instructive. One might expect little commonality between the two sets of lines due to the different modes of excitation, since the persistent lines refer to spark or arc excitation and MTES lines are excited by molecular energy transfer from a triplet species $N_2(A^3\Sigma^+)$. However, comparison of the above table with tabulated persistent lines³ yields the following results:

element	<u>Al</u>	<u>Cr</u>	<u>Fe</u>	<u>Mn</u>
MTES lines (nm)	309.2, 396.1	359.4, 357.9	344.1, 358.1	279.5, 403.1
persistent lines (nm)	309.2, 396.1	428.9, 425.4	302.1, 358.1	257.6, 403.1

One sees no discernable pattern. The Al MTES lines and persistent lines are identical. The Cr lines show no commonality. Fe and Mn are intermediate cases.

V. Future Activity

As per the program plans given in Appendix 2 the next quarter will be spent in completion of Tasks IABC for the elements Ti, V, and Si. Establishment of the Silicon vapor pressure curve is especially important for two reasons. First, the vapor pressure curves for the impurities will be the same as the one for Silicon if the vaporization process is congruent. Thus, they will not be the same as the vapor pressure curve measured for the pure element. For example, the vapor pressure curve measured for Aluminum over the pure metal will differ from that measured when the source is Silicon doped with Aluminum. This comparison is a major milestone and will require good baseline data. Secondly, the impurity level in a sample will be determined by the comparison of the intensity of an impurity MTES line to a Silicon MTES line. Therefore, normal behavior of the Silicon must be confirmed by measurements at closely spaced intervals of the source temperature.

VI. References

1. The term Metastable Transfer Emission Spectrometry, MTES, is somewhat more descriptive and is used synonymously with Analytical Photon Catalysis. See Rev. Sci. Instrum. 49, 1124 (1978).
2. Ralph Hultgren, et al., "Selected Values of Thermodynamic Properties of Metals and Alloys," John Wiley and Sons, Inc. (New York, 1963).
3. An. N. Nesmeyanov, "Vapor Pressures of The Elements," translated and edited by J.I. Carasso, Academic (New York, 1963).
4. C.H. Corliss and W.R. Bozman, "Experimental Transition Probabilities for Spectral Lines of Seventy Elements," (NBS Monograph 53, 1962).
5. M. Pinta, "Detection and Determination of Trace Elements," Ann Arbor Science Publishers, Inc. (Ann Arbor, Mich., 1962).

VII. Appendix 1

Estimation of Concentrations and Required Temperatures

From our experience with Bi and Pb we can estimate the concentrations of metal vapors produced in our apparatus at a given source temperature or conversely we can estimate the source temperature required to produce a given concentration of metal vapor. Both of these abilities are useful experimentally to bracket working temperatures, and they serve as consistency checks for the calibration data. This technique is best illustrated by the examples that follow.

Table 10.1 (S. Dushman, "Scientific Foundations of Vacuum Technique," Wiley 1966) shows rate of vaporization data for many metals. Selected data for Bi from this table is summarized in the first two columns below. The values in the fourth column are computed from the temperatures in the first column and used to determine the metal concentration from the MTES curve for Bismuth (taken from Applied Physics Letters 30, 407 (1977)) shown in Figure 10.

T(C)	Rate of Evaporation gr/cm ² -sec	Metal Concentration Determined by MTES cm ³	10 ⁴ /T(K)
Bismuth 578	3 x 10 ⁻⁵	10 ⁹	11.75
508	3 x 10 ⁻⁶	10 ⁸	12.8
450	3 x 10 ⁻⁷	10 ⁷	13.83
	3 x 10 ⁻⁸ *	10 ⁶	14.8
	3 x 10 ⁻⁹ *	10 ⁵	15.8

If we assume that the concentrations of two different materials will be the same in the observation zone if their vaporization rates are the same, we can calculate the temperature required to produce a given concentration. For example, in Figure 10 the round data points were taken with the atomic absorption technique. This technique is limited to approximately 10⁹ atoms per cm³. For Bismuth 10⁹ atoms per cm³ is produced in our apparatus at a source temperature of 850(K) or 580(C); we determine this from Figure 10 by observing that 10⁴/T(K) equals 11.75 when the Bi concentration equals 10⁹ per cm³. From the table given previously we see that a rate of vaporization of 3 x 10⁻⁵ gr/cm²-sec is responsible for this concentration. Using our assumption we can now estimate the temperature required to produce 10⁹ atoms per cm³ of any metal. Since atomic absorption is insensitive to concentrations much lower than this, our estimated temperature will have to be maintained in order to calibrate our apparatus by the AA method. Using table 10.1 we extract the following information on the metals of interest to our project.

*values obtained by extrapolation from table 10.1

Metal	T(C) required for rate of vaporization (3×10^{-5} gr/cm ² -sec) to sustain 10^5 atoms per cm ³
Al	1080
Cr	1300
Fe	1400
Mn	900
* Mo	2500
Si	1400
* Ti	1600
* V	1780
* Zr	2250

Since our apparatus is capable of sustaining a maximum temperature of 1600C, the materials marked with an asterisk cannot be calibrated with AA methods. Ti is a borderline case. In addition V, Zr and Mo have such low rates of vaporization at 1600C that more sophisticated sources will be required if we are to study the pure vapors of these materials.

We can also use our rate of vaporization technique to estimate concentrations at various temperatures. This was done for Aluminum in the progress report for October and serves as an example here. Our lowest detectable MTES signal for Al (See Figure 3) was at $10^4/T(K)$ equal to 9.4 or T(C) equal to 790. From table 10.1 the extrapolated Aluminum rate of vaporization at 790C is approximately 9×10^{-9} gr/cm²-sec. If we assume that Al and Bismuth are detected with equivalent sensitivity by MTES, then we can use the Bismuth table given above to estimate our Aluminum detectivity at 5×10^5 atoms per cm³. When applied to Chromium this method gives a sensitivity 3×10^5 atoms per cm³. The method of calibration by AA gives approximately 2×10^5 . This technique was also used to estimate the sensitivity to Iron.

TABLE 10.1
Temperatures for Given Values of P_μ and Corresponding Rates of Evaporation

Metal	Ref.	Data Temp. Range (°C)	t (°C) and W	$P_\mu =$						t_m	P_μ	t_B
				10^{-2}	10^{-1}	1	10	100	1000			
Li	4	459-1080	t : 348 W : $6.17 \cdot 10^{-8}$	399 $5.93 \cdot 10^{-7}$	460 $5.68 \cdot 10^{-6}$	534 $5.41 \cdot 10^{-5}$	623 $5.13 \cdot 10^{-4}$	737 $4.84 \cdot 10^{-3}$	181			1331
Na	4	264-928	t : 158 W : $1.35 \cdot 10^{-7}$	195 $1.29 \cdot 10^{-6}$	238 $1.24 \cdot 10^{-5}$	290 $1.18 \cdot 10^{-4}$	355 $1.12 \cdot 10^{-3}$	437 $1.05 \cdot 10^{-2}$	98	10^{-4}		890
K	4	100-760	t : 91 W : $1.91 \cdot 10^{-7}$	123 $1.83 \cdot 10^{-6}$	162 $1.75 \cdot 10^{-5}$	208 $1.66 \cdot 10^{-4}$	266 $1.57 \cdot 10^{-3}$	341 $1.47 \cdot 10^{-2}$	64	$9 \cdot 10^{-4}$		766
Rb	4	...	t : 64 W : $2.94 \cdot 10^{-7}$	95 $2.81 \cdot 10^{-6}$	133 $2.68 \cdot 10^{-5}$	176 $2.55 \cdot 10^{-4}$	228 $2.41 \cdot 10^{-3}$	300 $2.22 \cdot 10^{-2}$	39	$2.6 \cdot 10^{-3}$		701
Cs	4	...	t : 46 W : $3.77 \cdot 10^{-7}$	75 $3.61 \cdot 10^{-6}$	110 $3.44 \cdot 10^{-5}$	152 $3.26 \cdot 10^{-4}$	206 $3.07 \cdot 10^{-3}$	277 $2.87 \cdot 10^{-2}$	30	$2.6 \cdot 10^{-3}$		685
Cu	4	969-1606	t : 942 W : $1.33 \cdot 10^{-7}$	1032 $1.29 \cdot 10^{-6}$	1142 $1.24 \cdot 10^{-5}$	1272 $1.18 \cdot 10^{-4}$	1427 $1.13 \cdot 10^{-3}$	1622 $1.07 \cdot 10^{-2}$	1084	0.26		2578
Ag	4	721-1000	t : 757 W : $1.89 \cdot 10^{-7}$	832 $1.82 \cdot 10^{-6}$	922 $1.75 \cdot 10^{-5}$	1032 $1.68 \cdot 10^{-4}$	1167 $1.60 \cdot 10^{-3}$	1337 $1.51 \cdot 10^{-2}$	961	2.5		2162
Au	4	727-987	t : 987 W : $2.31 \cdot 10^{-7}$	1082 $2.26 \cdot 10^{-6}$	1197 $2.14 \cdot 10^{-5}$	1332 $2.05 \cdot 10^{-4}$	1507 $1.94 \cdot 10^{-3}$	1707 $1.84 \cdot 10^{-2}$	1063	$5 \cdot 10^{-2}$		2709
Be	4	899-1279	t : 902 W : $5.11 \cdot 10^{-8}$	987 $4.93 \cdot 10^{-7}$	1092 $4.74 \cdot 10^{-6}$	1212 $4.55 \cdot 10^{-5}$	1367 $4.33 \cdot 10^{-4}$	1567 $4.08 \cdot 10^{-3}$	1283	28		2097
Mg	4	736-1020	t : 287 W : $1.22 \cdot 10^{-7}$	330 $1.17 \cdot 10^{-6}$	382 $1.12 \cdot 10^{-5}$	442 $1.08 \cdot 10^{-4}$	517 $1.02 \cdot 10^{-3}$	612 $0.97 \cdot 10^{-2}$	650	$2.5 \cdot 10^{-3}$		1104
Ca	4	527-647	t : 402 W : $1.42 \cdot 10^{-7}$	452 $1.37 \cdot 10^{-6}$	517 $1.31 \cdot 10^{-5}$	592 $1.26 \cdot 10^{-4}$	687 $1.19 \cdot 10^{-3}$	817 $1.12 \cdot 10^{-2}$	850	$1.9 \cdot 10^{-3}$		1492
Sr	4	...	t : 342 W : $2.20 \cdot 10^{-7}$	394 $2.11 \cdot 10^{-6}$	456 $2.02 \cdot 10^{-5}$	531 $1.93 \cdot 10^{-4}$	623 $1.82 \cdot 10^{-3}$	742 $1.71 \cdot 10^{-2}$	770	$1.8 \cdot 10^{-3}$		1367
Ba	4	1060-138	t : 417 W : $2.60 \cdot 10^{-7}$	467 $2.51 \cdot 10^{-6}$	537 $2.40 \cdot 10^{-5}$	617 $2.28 \cdot 10^{-4}$	727 $2.16 \cdot 10^{-3}$	867 $2.03 \cdot 10^{-2}$	710	$7 \cdot 10^{-4}$		1637
Zn	4	239-377	t : 208 W : $2.15 \cdot 10^{-7}$	246 $2.07 \cdot 10^{-6}$	290 $1.99 \cdot 10^{-5}$	342 $1.90 \cdot 10^{-4}$	405 $1.81 \cdot 10^{-3}$	485 $1.71 \cdot 10^{-2}$	420	$1.2 \cdot 10^{-3}$		906
Cd	4	200-260	t : 149 W : $3.01 \cdot 10^{-7}$	182 $2.90 \cdot 10^{-6}$	221 $2.78 \cdot 10^{-5}$	267 $2.66 \cdot 10^{-4}$	321 $2.54 \cdot 10^{-3}$	392 $2.44 \cdot 10^{-2}$	321	10^{-2}		765
Hg	4	...	t : -28 W : $5.28 \cdot 10^{-7}$	-8 $5.08 \cdot 10^{-6}$	16 $4.86 \cdot 10^{-5}$	45 $4.63 \cdot 10^{-4}$	81 $4.39 \cdot 10^{-3}$	125 $4.14 \cdot 10^{-2}$	-39	$2.6 \cdot 10^{-3}$		357
B	4	...	t : 1687 W : $4.33 \cdot 10^{-8}$	1827 $4.19 \cdot 10^{-7}$	1977 $4.05 \cdot 10^{-6}$	2157 $3.89 \cdot 10^{-5}$	2377 $3.73 \cdot 10^{-4}$	2657 $3.55 \cdot 10^{-3}$	2027	2		3927
Al	4	1137-1195	t : 882 W : $8.92 \cdot 10^{-8}$	972 $8.59 \cdot 10^{-7}$	1082 $8.23 \cdot 10^{-6}$	1207 $7.88 \cdot 10^{-5}$	1347 $7.53 \cdot 10^{-4}$	1547 $7.10 \cdot 10^{-3}$	659	...		2447
Sc	SD*	...	t : 1058 W : $1.56 \cdot 10^{-7}$	1161 $1.69 \cdot 10^{-6}$	1282 $1.62 \cdot 10^{-5}$	1423 $1.55 \cdot 10^{-4}$	1595 $1.48 \cdot 10^{-3}$	1804 $1.40 \cdot 10^{-2}$	1397	6.6		2400†
Y	SD*	...	t : 1249 W : $2.00 \cdot 10^{-7}$	1362 $1.92 \cdot 10^{-6}$	1494 $1.83 \cdot 10^{-5}$	1649 $1.74 \cdot 10^{-4}$	1833 $1.65 \cdot 10^{-3}$	2056 $1.55 \cdot 10^{-2}$	1477	0.76		3087
La	4	1327-1627	t : 1262 W : $1.56 \cdot 10^{-7}$	1377 $1.69 \cdot 10^{-6}$	1527 $1.62 \cdot 10^{-5}$	1697 $1.55 \cdot 10^{-4}$	1897 $1.48 \cdot 10^{-3}$	2147 $1.40 \cdot 10^{-2}$	920	...		3367
Ce	SD*	...	t : 1004 W : $2.00 \cdot 10^{-7}$	1091 $1.92 \cdot 10^{-6}$	1190 $1.83 \cdot 10^{-5}$	1305 $1.74 \cdot 10^{-4}$	1439 $1.65 \cdot 10^{-3}$	1599 $1.55 \cdot 10^{-2}$	785	$5.5 \cdot 10^{-6}$		1400†
Nd	4	899-1279	t : 957 W : $2.00 \cdot 10^{-7}$	1062 $1.92 \cdot 10^{-6}$	1192 $1.83 \cdot 10^{-5}$	1342 $1.74 \cdot 10^{-4}$	1537 $1.65 \cdot 10^{-3}$	1777 $1.55 \cdot 10^{-2}$	1024	$4.2 \cdot 10^{-3}$		3087
Ga	4	957-1245	t : 757 W : $1.52 \cdot 10^{-7}$	842 $1.46 \cdot 10^{-6}$	937 $1.40 \cdot 10^{-5}$	1057 $1.34 \cdot 10^{-4}$	1197 $1.27 \cdot 10^{-3}$	1372 $1.22 \cdot 10^{-2}$	37	...		2237
In	4	727-1075	t : 670 W : $2.04 \cdot 10^{-7}$	747 $1.96 \cdot 10^{-6}$	837 $1.88 \cdot 10^{-5}$	947 $1.79 \cdot 10^{-4}$	1077 $1.70 \cdot 10^{-3}$	1242 $1.61 \cdot 10^{-2}$	156	...		2091
Tl	4	...	t : 412 W : $3.19 \cdot 10^{-7}$	468 $3.06 \cdot 10^{-6}$	535 $2.93 \cdot 10^{-5}$	615 $2.80 \cdot 10^{-4}$	713 $2.66 \cdot 10^{-3}$	837 $2.50 \cdot 10^{-2}$	304	$3 \cdot 10^{-3}$		1467
C	4	2084-2597	t : 1977 W : $4.27 \cdot 10^{-8}$	2107 $4.14 \cdot 10^{-7}$	2247 $4.03 \cdot 10^{-6}$	2427 $3.89 \cdot 10^{-5}$	2627 $3.76 \cdot 10^{-4}$	2867 $3.61 \cdot 10^{-3}$	...	...		(3927)
Si	4	...	t : 1177 W : $8.12 \cdot 10^{-8}$	1282 $7.84 \cdot 10^{-7}$	1357 $7.54 \cdot 10^{-6}$	1547 $7.24 \cdot 10^{-5}$	1717 $6.93 \cdot 10^{-4}$	1927 $6.59 \cdot 10^{-3}$	1415	1		2787
Ti	Morrison	1111-1323	t : 1321 W : $1.01 \cdot 10^{-7}$	1431 $0.98 \cdot 10^{-6}$	1558 $0.94 \cdot 10^{-5}$	1703 $0.90 \cdot 10^{-4}$	1877 $0.86 \cdot 10^{-3}$	2083 $0.82 \cdot 10^{-2}$	1800	...		>3000†
Zr	4	1676-1781	t : 1837 W : $1.21 \cdot 10^{-7}$	2002 $1.17 \cdot 10^{-6}$	2187 $1.12 \cdot 10^{-5}$	2397 $1.08 \cdot 10^{-4}$	2647 $1.03 \cdot 10^{-3}$	2977 $0.98 \cdot 10^{-2}$	1852	10^{-2}		4405
Th	SD*	...	t : 1686 W : $2.01 \cdot 10^{-7}$	1831 $1.94 \cdot 10^{-6}$	1999 $1.86 \cdot 10^{-5}$	2196 $1.79 \cdot 10^{-4}$	2431 $1.71 \cdot 10^{-3}$	2715 $1.63 \cdot 10^{-2}$	1827	$9.3 \cdot 10^{-2}$		4500†
Ge	4	1237-1612	t : 1037 W : $1.37 \cdot 10^{-7}$	1142 $1.32 \cdot 10^{-6}$	1262 $1.27 \cdot 10^{-5}$	1407 $1.21 \cdot 10^{-4}$	1582 $1.15 \cdot 10^{-3}$	1797 $1.09 \cdot 10^{-2}$	937	$7 \cdot 10^{-4}$		2827

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Vapor Pressures and Rates of Evaporation

Ch. 10

Sect. 10.2

Vapor-Pressure Data and Rates of Evaporation

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TABLE 10.1 (Continued)

Metal	Ref.	Data Temp. Range (°C)	t (°C) and W	$P_{\mu} =$						t_m	P_{μ}	t_B
				10^{-8}	10^{-3}	1	10	100	1000			
Sn	4	1151-1415	t : 882		977	1092	1227	1397	1612	232	...	2679
Pb	4	...	W : $1.67 \cdot 10^{-7}$	$1.80 \cdot 10^{-6}$	$1.72 \cdot 10^{-5}$	$1.64 \cdot 10^{-4}$	$1.56 \cdot 10^{-3}$	$1.46 \cdot 10^{-2}$		328	...	1751
V	4	1389-1609	t : 487		551	627	719	832	977	1857	10	3377
Cb	SD*	...	W : $3.05 \cdot 10^{-7}$	$2.93 \cdot 10^{-6}$	$2.80 \cdot 10^{-5}$	$2.67 \cdot 10^{-4}$	$2.53 \cdot 10^{-3}$	$2.38 \cdot 10^{-2}$		2500*	0.6	3700†
Ta	4	1727-2997	t : 1432		1551	1687	1847	2037	2287	2997	6	5427
P ₄	4	...	W : $1.01 \cdot 10^{-7}$	$0.98 \cdot 10^{-6}$	$0.94 \cdot 10^{-5}$	$0.90 \cdot 10^{-4}$	$0.87 \cdot 10^{-3}$	$0.82 \cdot 10^{-2}$		597	...	431
Sb ₃	4	...	t : 2194		2355	2539	...	...	...	630	10 ²	1637
Bi	4	409-497	W : $1.16 \cdot 10^{-7}$	$1.08 \cdot 10^{-6}$	$1.06 \cdot 10^{-5}$	$1.07 \cdot 10^{-4}$	$1.03 \cdot 10^{-3}$	$0.98 \cdot 10^{-2}$		271	...	1559
Cr	4	889-1288	t : 2397		2587	2807	3067	3372	3737	1903	$5.5 \cdot 10^{-3}$	2665
Mo	4	1797-2231	W : $1.52 \cdot 10^{-7}$	$1.47 \cdot 10^{-6}$	$1.41 \cdot 10^{-5}$	$1.36 \cdot 10^{-4}$	$1.30 \cdot 10^{-3}$	$1.24 \cdot 10^{-2}$		2577	8	4827
W	4	...	t : 107		130	157	187	222	262	3377	$2 \cdot 10$	5527
U	4	1357-1697	W : $3.3 \cdot 10^{-7}$	$3.24 \cdot 10^{-6}$	$3.13 \cdot 10^{-5}$	$3.03 \cdot 10^{-4}$	$2.92 \cdot 10^{-3}$	$2.81 \cdot 10^{-2}$		1130	10^{-3}	3927
			t : 382		477	542	617	757				
			W : $2.52 \cdot 10^{-7}$	$2.43 \cdot 10^{-6}$	$2.35 \cdot 10^{-5}$	$2.26 \cdot 10^{-4}$	$2.16 \cdot 10^{-3}$	$2.01 \cdot 10^{-2}$				
			t : 450		508	578	661	762	892			
			W : $3.14 \cdot 10^{-7}$	$3.02 \cdot 10^{-6}$	$2.89 \cdot 10^{-5}$	$2.76 \cdot 10^{-4}$	$2.62 \cdot 10^{-3}$	$2.47 \cdot 10^{-2}$				
			t : 1062		1162	1267	1392	1557	1737			
			W : $1.15 \cdot 10^{-7}$	$1.11 \cdot 10^{-6}$	$1.07 \cdot 10^{-5}$	$1.03 \cdot 10^{-4}$	$0.98 \cdot 10^{-3}$	$0.94 \cdot 10^{-2}$				
			t : 1987		2167	2377	2627	2927	3297			
			W : $1.20 \cdot 10^{-7}$	$1.16 \cdot 10^{-6}$	$1.11 \cdot 10^{-5}$	$1.06 \cdot 10^{-4}$	$1.01 \cdot 10^{-3}$	$0.95 \cdot 10^{-2}$				
			t : 2547		2757	3007	3297	3647				
			W : $1.49 \cdot 10^{-7}$	$1.44 \cdot 10^{-6}$	$1.38 \cdot 10^{-5}$	$1.32 \cdot 10^{-4}$	$1.26 \cdot 10^{-3}$					
			t : 1442		1582	1737	1927	2157				
			W : $2.17 \cdot 10^{-7}$	$2.09 \cdot 10^{-6}$	$2.01 \cdot 10^{-5}$	$1.92 \cdot 10^{-4}$	$1.83 \cdot 10^{-3}$	$1.73 \cdot 10^{-2}$				
Se	4	...	t : 144		167	197	232	277	347	217	3.2	685
Te ₈	4	...	W : $2.54 \cdot 10^{-7}$	$2.47 \cdot 10^{-6}$	$2.39 \cdot 10^{-5}$	$2.31 \cdot 10^{-4}$	$2.21 \cdot 10^{-3}$	$2.08 \cdot 10^{-2}$		450	$1.6 \cdot 10^{-2}$	987
Po	4	438-745	t : 261		296	336	385	438	520	254	$8 \cdot 10^{-1}$	962
Mn	4	...	W : $4.03 \cdot 10^{-7}$	$3.91 \cdot 10^{-6}$	$3.78 \cdot 10^{-5}$	$3.64 \cdot 10^{-4}$	$3.50 \cdot 10^{-3}$	$3.31 \cdot 10^{-2}$		1244	$1.2 \cdot 10^{-3}$	2051
Re	4	...	t : 187		220	263	314	382	472	3180	25	5627
Fe	4	1092-1246	W : $3.94 \cdot 10^{-7}$	$3.81 \cdot 10^{-6}$	$3.65 \cdot 10^{-5}$	$3.49 \cdot 10^{-4}$	$3.30 \cdot 10^{-3}$	$3.10 \cdot 10^{-2}$		1539	30	2857
Co	4	1090-1249	t : 697		767	852	947	1067	1227	1495	67	2877
Ni	4	1034-1310	W : $1.39 \cdot 10^{-7}$	$1.34 \cdot 10^{-6}$	$1.29 \cdot 10^{-5}$	$1.24 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.12 \cdot 10^{-2}$		1452	5	2839
Ru	SD*	...	t : 2367		2557	2787	3057	3397	...	2427	9.8	...
Rh	4	...	W : $1.55 \cdot 10^{-7}$	$1.50 \cdot 10^{-6}$	$1.44 \cdot 10^{-5}$	$1.38 \cdot 10^{-4}$	$1.31 \cdot 10^{-3}$			1966	5.5	(3727)
Pd	4	...	t : 1107		1207	1322	1467	1637	1847	1550	11	3127
Os	SD	...	W : $1.17 \cdot 10^{-7}$	$1.13 \cdot 10^{-6}$	$1.09 \cdot 10^{-5}$	$1.05 \cdot 10^{-4}$	$0.99 \cdot 10^{-3}$	$0.95 \cdot 10^{-2}$		2697	...	> 5300†
Ir	4	...	t : 1162		1262	1377	1517	1697	1907	1770	$1.7 \cdot 10^{-1}$	3827
Pt	4	...	W : $1.18 \cdot 10^{-7}$	$1.14 \cdot 10^{-6}$	$1.10 \cdot 10^{-5}$	$1.06 \cdot 10^{-4}$	$1.01 \cdot 10^{-3}$	$0.96 \cdot 10^{-2}$				
			t : 1142		1247	1357	1497	1667	1877			
			W : $1.19 \cdot 10^{-7}$	$1.15 \cdot 10^{-6}$	$1.11 \cdot 10^{-5}$	$1.06 \cdot 10^{-4}$	$1.01 \cdot 10^{-3}$	$0.96 \cdot 10^{-2}$				
			t : 1913		2058	2230	2431	2666	2946			
			W : $1.26 \cdot 10^{-7}$	$1.22 \cdot 10^{-6}$	$1.18 \cdot 10^{-5}$	$1.13 \cdot 10^{-4}$	$1.08 \cdot 10^{-3}$	$1.04 \cdot 10^{-2}$				
			t : 1587		1707	1857	2027	2247	2527			
			W : $1.37 \cdot 10^{-7}$	$1.33 \cdot 10^{-6}$	$1.28 \cdot 10^{-5}$	$1.23 \cdot 10^{-4}$	$1.18 \cdot 10^{-3}$	$1.12 \cdot 10^{-2}$				
			t : 1157		1262	1387	1547	1727	1967			
			W : $1.59 \cdot 10^{-7}$	$1.54 \cdot 10^{-6}$	$1.48 \cdot 10^{-5}$	$1.41 \cdot 10^{-4}$	$1.35 \cdot 10^{-3}$	$1.27 \cdot 10^{-2}$				
			t : 2101		2264	2451	2667	2920	3221			
			W : $1.65 \cdot 10^{-7}$	$1.60 \cdot 10^{-6}$	$1.54 \cdot 10^{-5}$	$1.48 \cdot 10^{-4}$	$1.42 \cdot 10^{-3}$	$1.36 \cdot 10^{-2}$				
			t : 1797		1947	2107	2307	2527	2827			
			W : $1.78 \cdot 10^{-7}$	$1.72 \cdot 10^{-6}$	$1.66 \cdot 10^{-5}$	$1.60 \cdot 10^{-4}$	$1.53 \cdot 10^{-3}$	$1.46 \cdot 10^{-2}$				
			t : 1602		1742	1907	2077	2317	2587			
			W : $1.88 \cdot 10^{-7}$	$1.82 \cdot 10^{-6}$	$1.75 \cdot 10^{-5}$	$1.68 \cdot 10^{-4}$	$1.60 \cdot 10^{-3}$	$1.52 \cdot 10^{-2}$				

* SD = Dushman, 1st edition of this book.

† Handbook of Chemistry and Physics, 39th edition.

VIII. Appendix 2
Program Plans
and
Reporting Schedule

1978 (Week Ending Sunday Dates)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
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1978 (Week Ending Sunday Dates)

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1 8 15 22 29	5 12 19 26	2 9 16 23 30	7 14 21 28	4 11 18 25	2 9 16 23 30	6 13 20 27	3 10 17 24	+	8 15 22 29	5 12 19 26	3 10 17 24 31

[illegible]

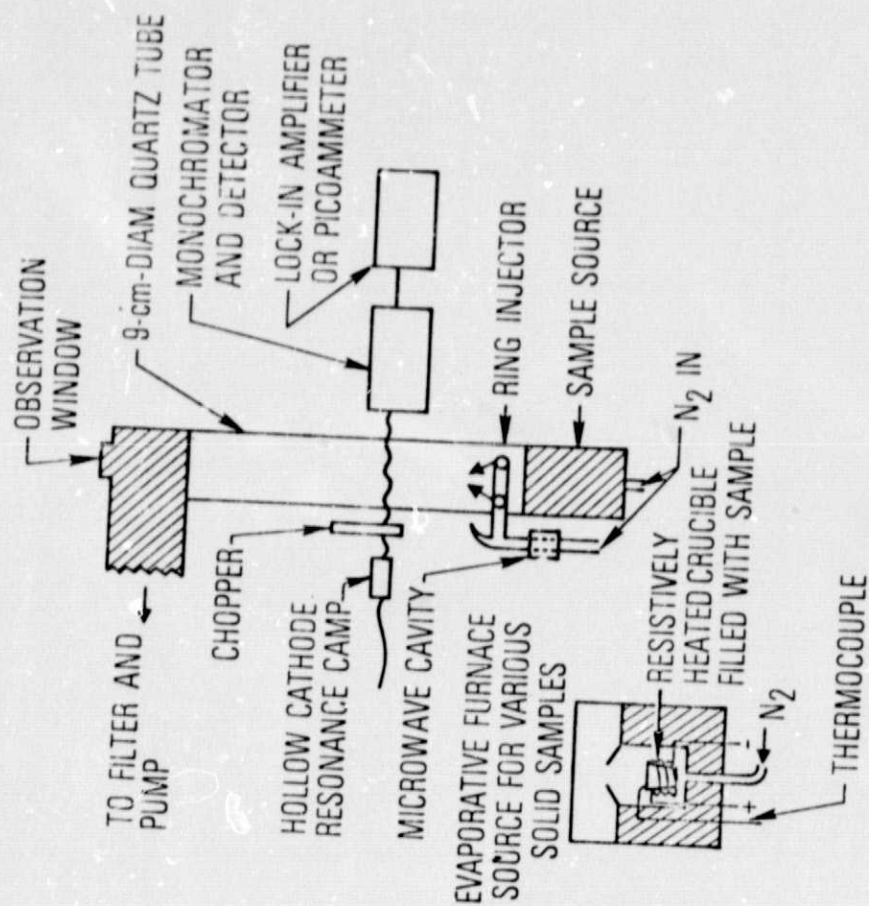


Figure 1: Schematic for MTES Apparatus

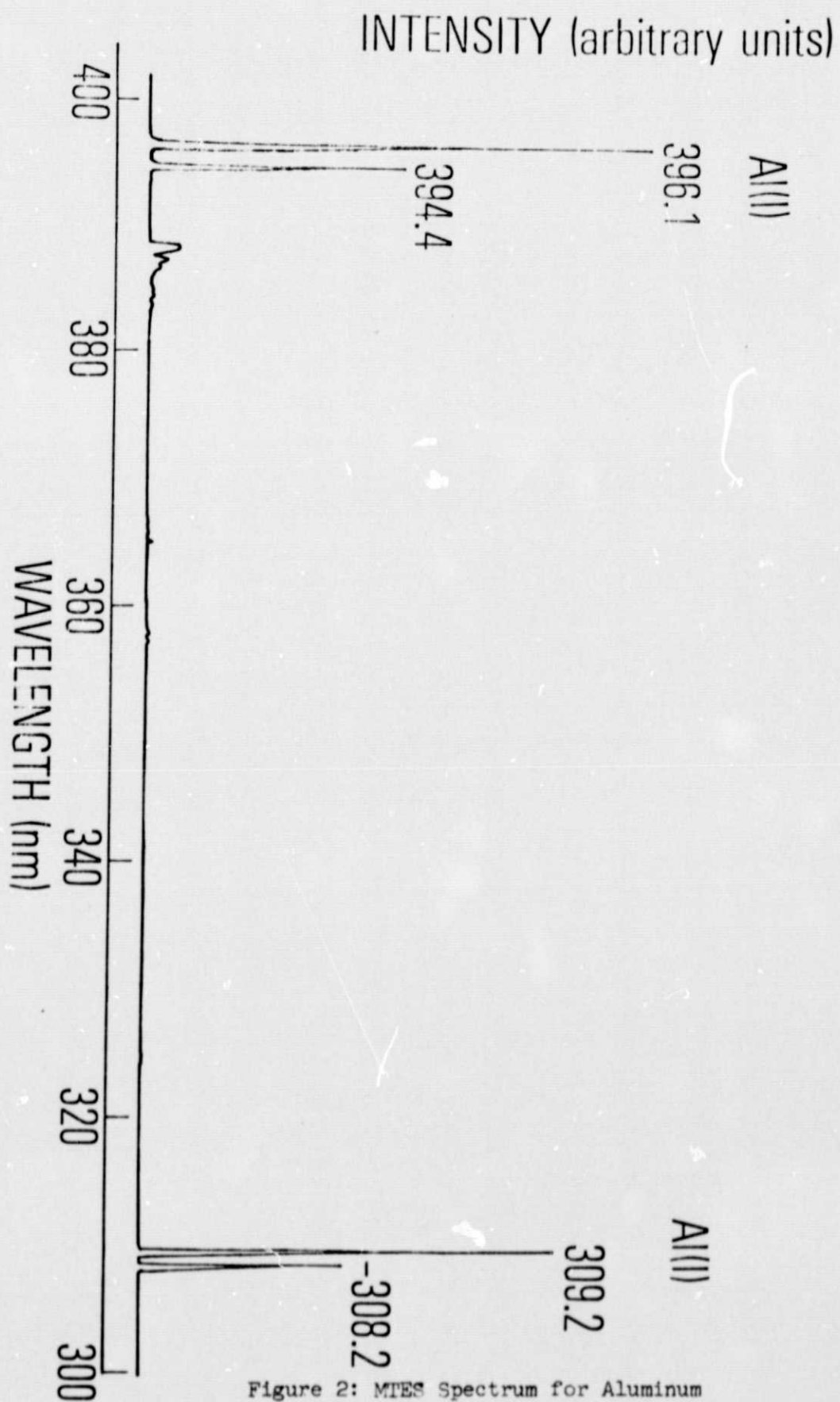


Figure 2: MIES Spectrum for Aluminum

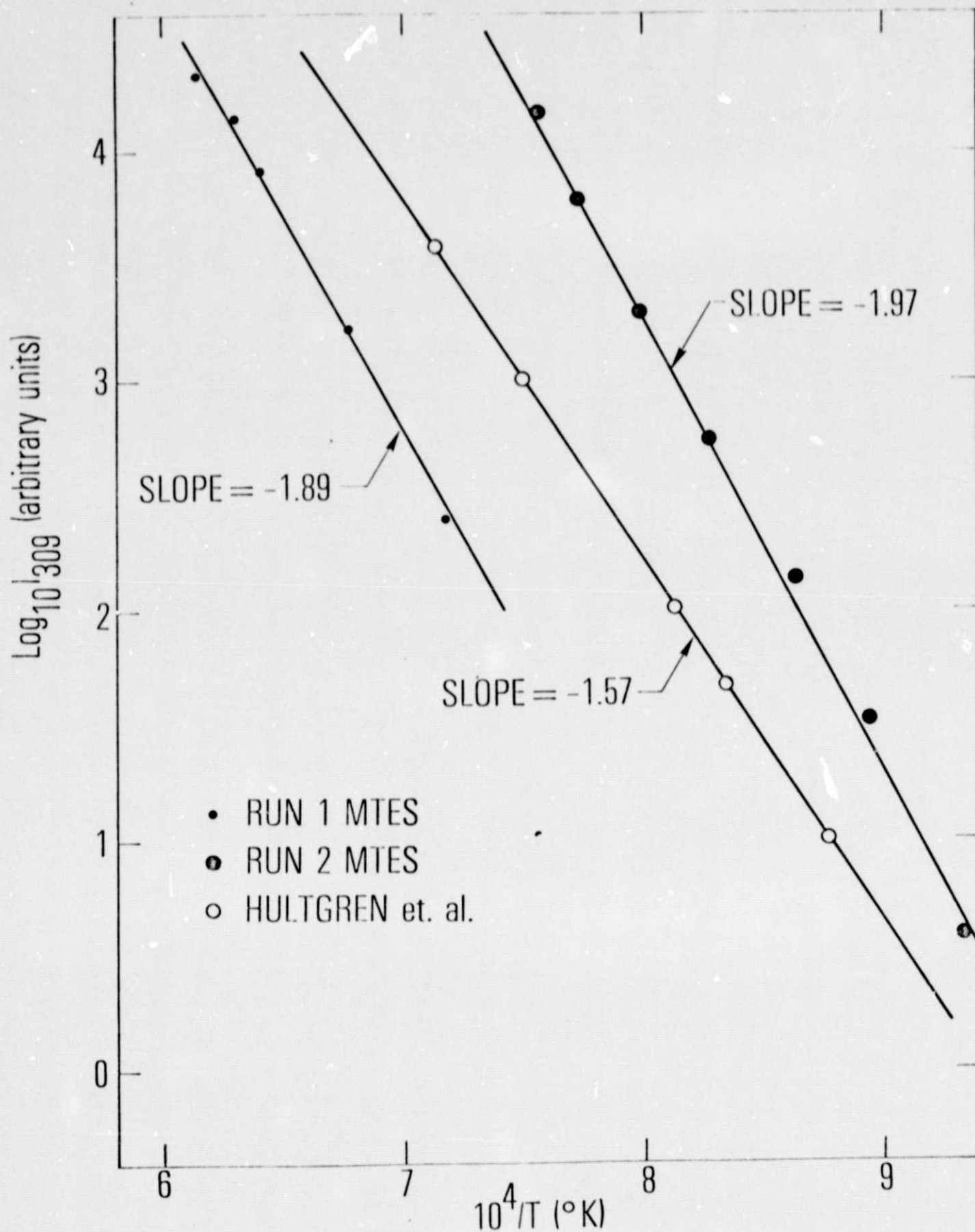


Figure 3: MTES Vapor Pressure Curve for Aluminum at 309 nm

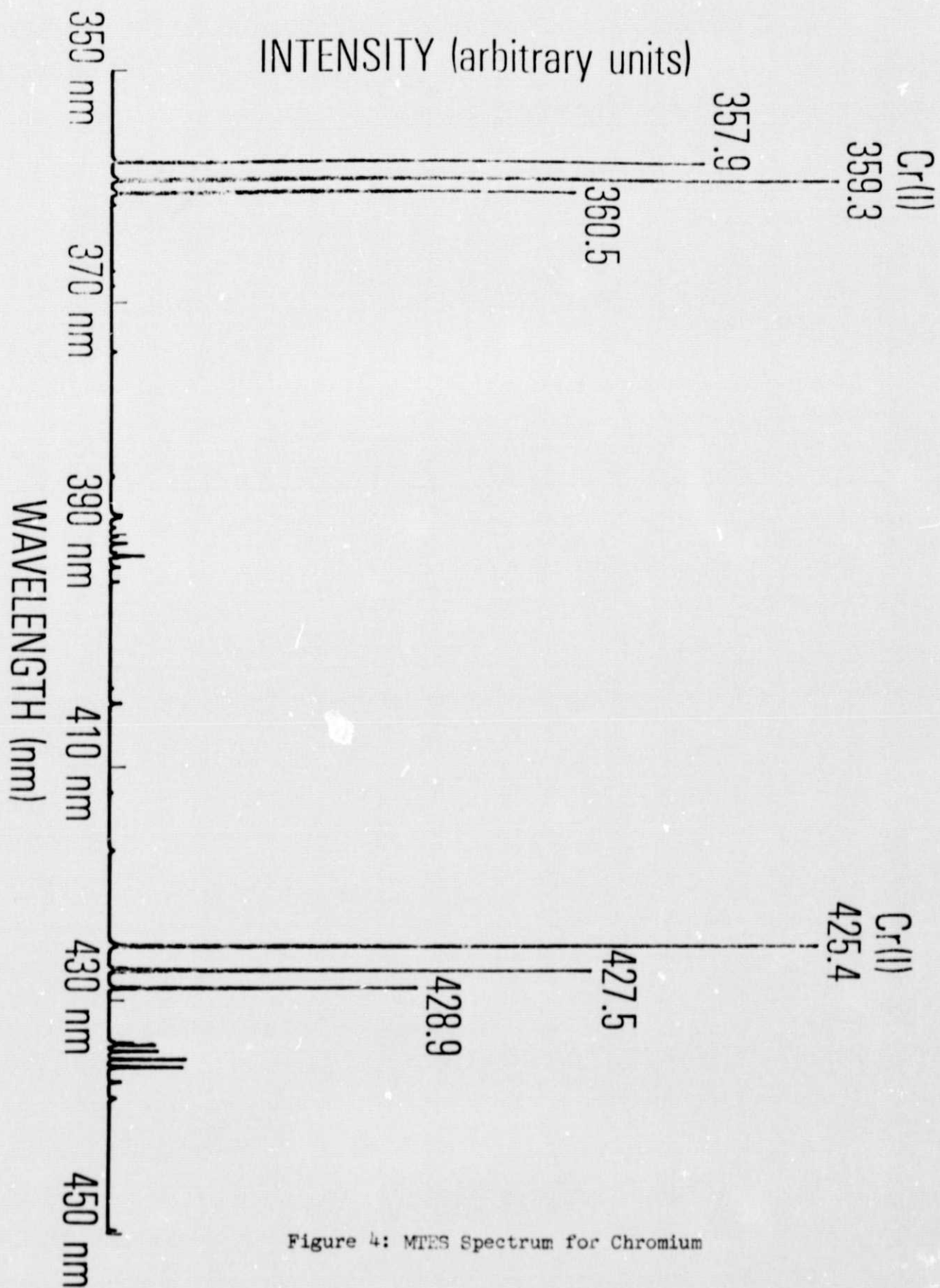


Figure 4: MTES Spectrum for Chromium

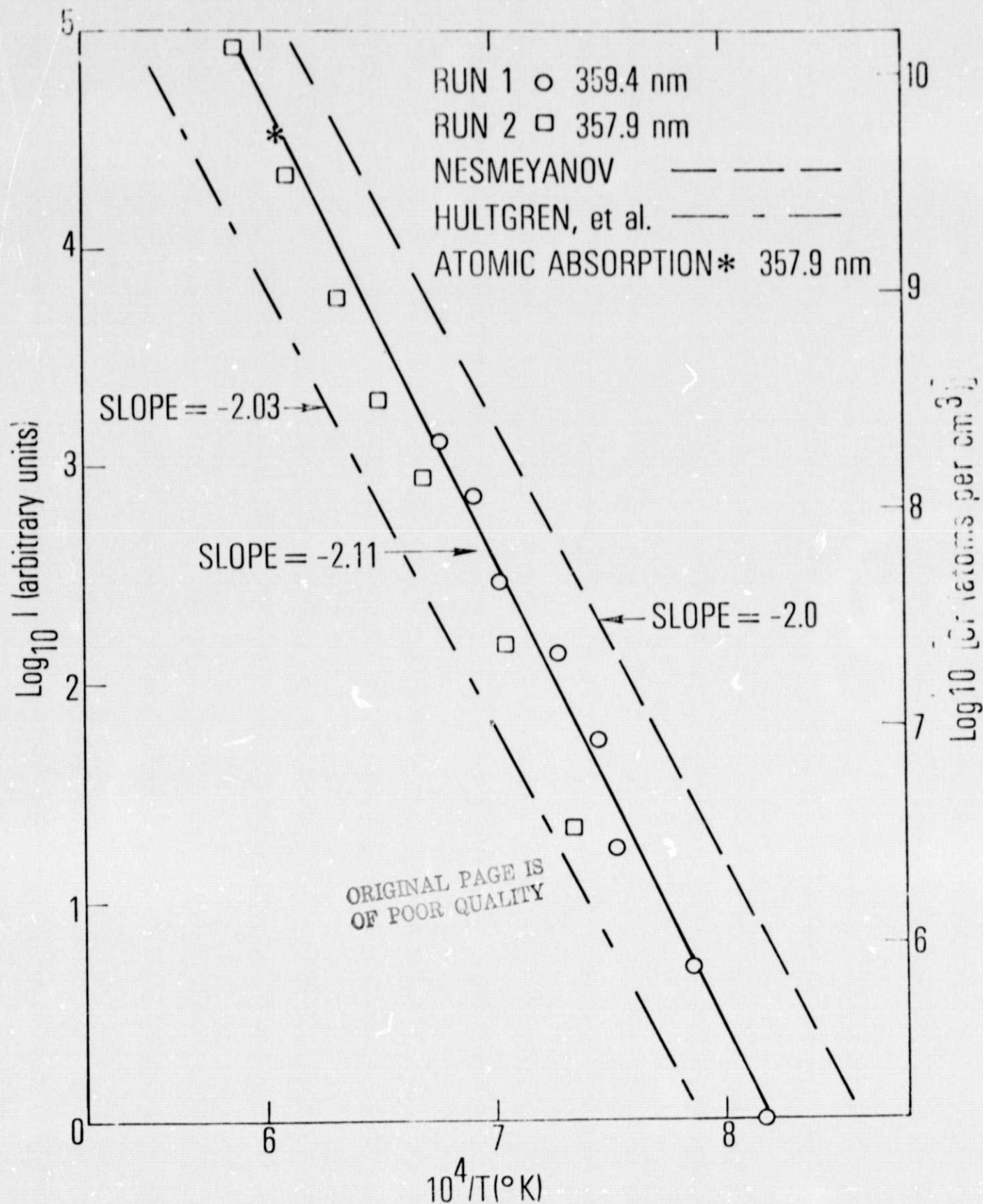


Figure 5: MTES Vapor Pressure Curve for Chromium

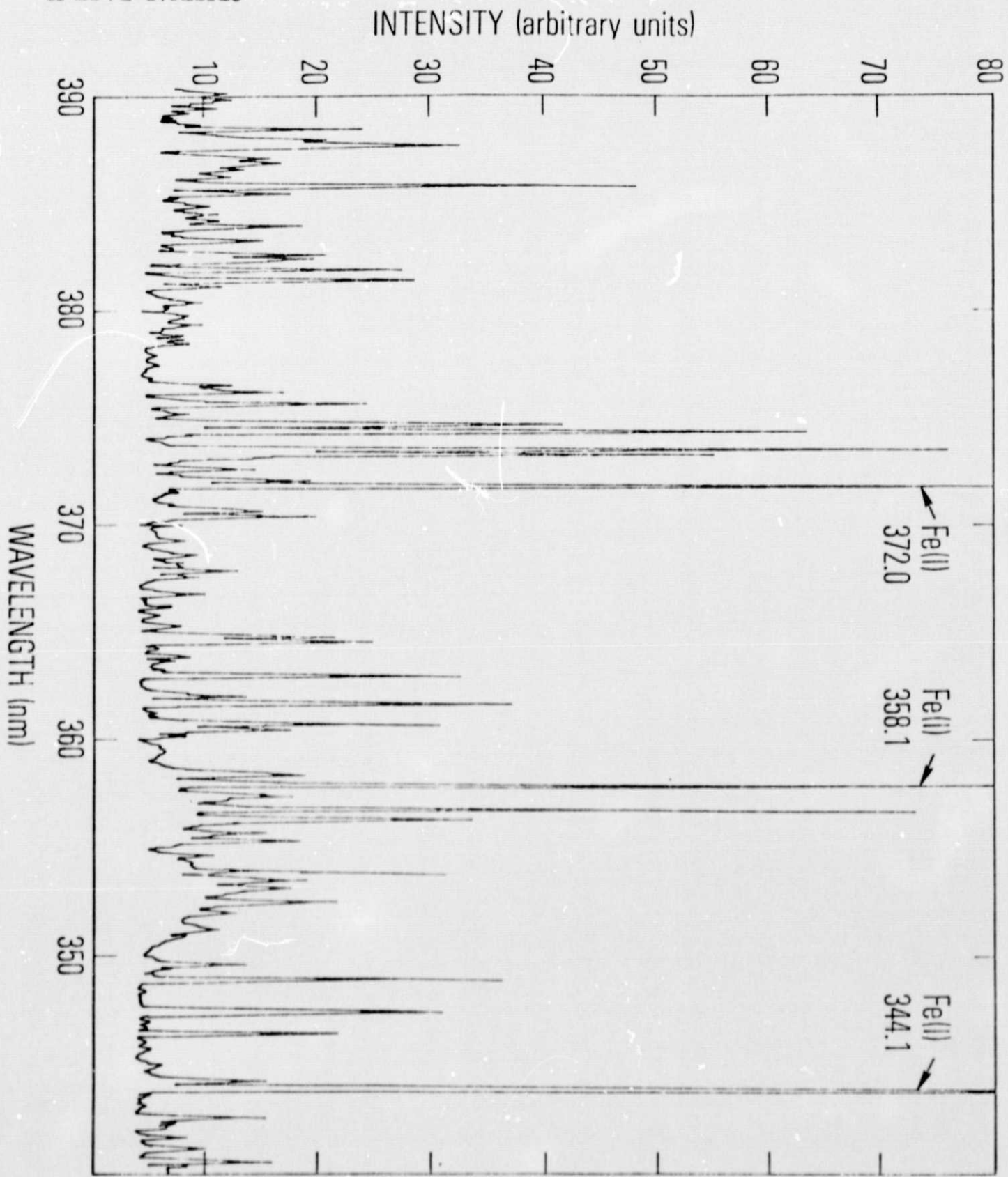


Figure 6: MTES Spectrum for Iron

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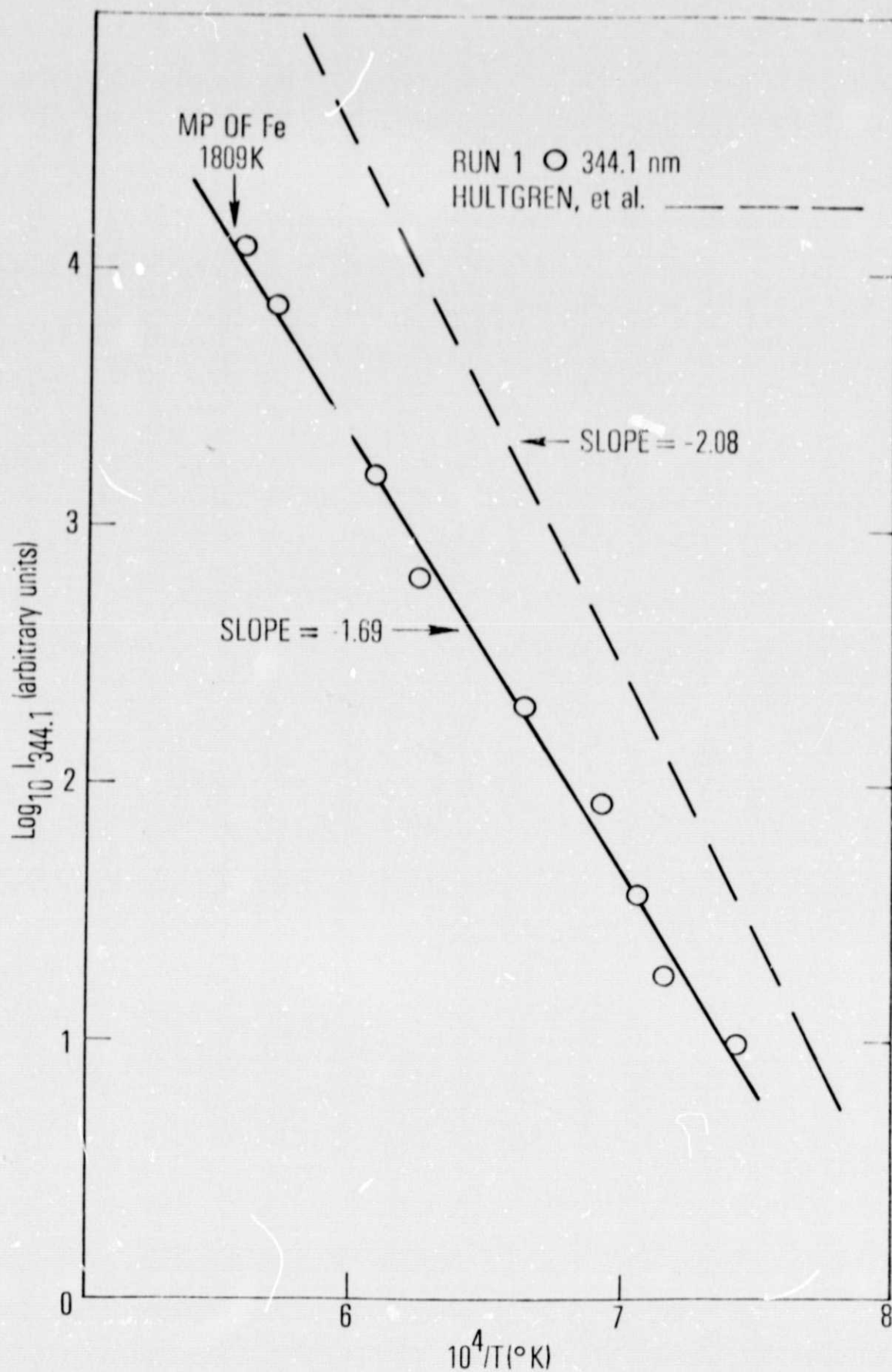


Figure 7: MTES Vapor Pressure Curve for Iron at 344.1 nm

INTENSITY (arbitrary units)

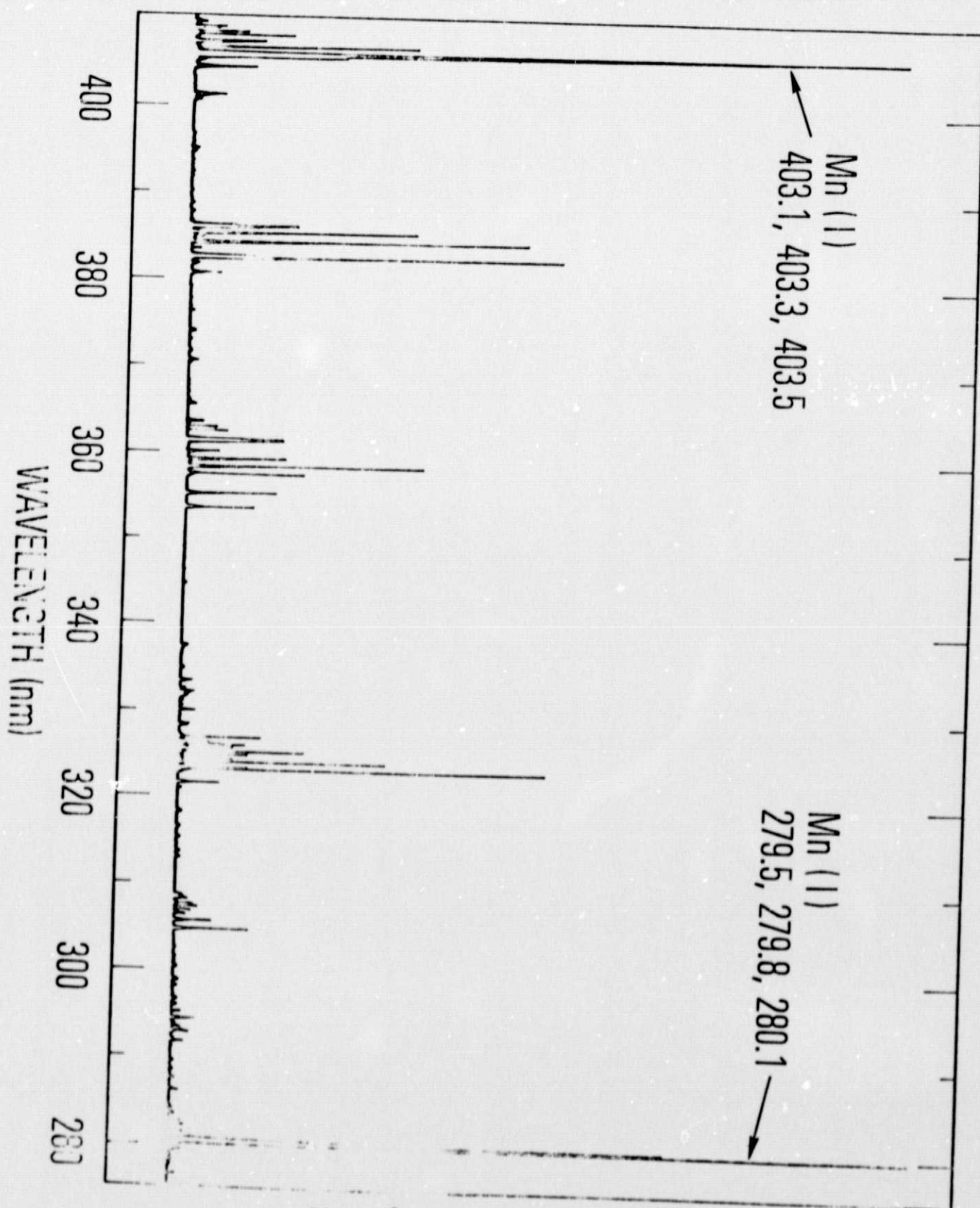


Figure 8: MTES Spectrum for Manganese

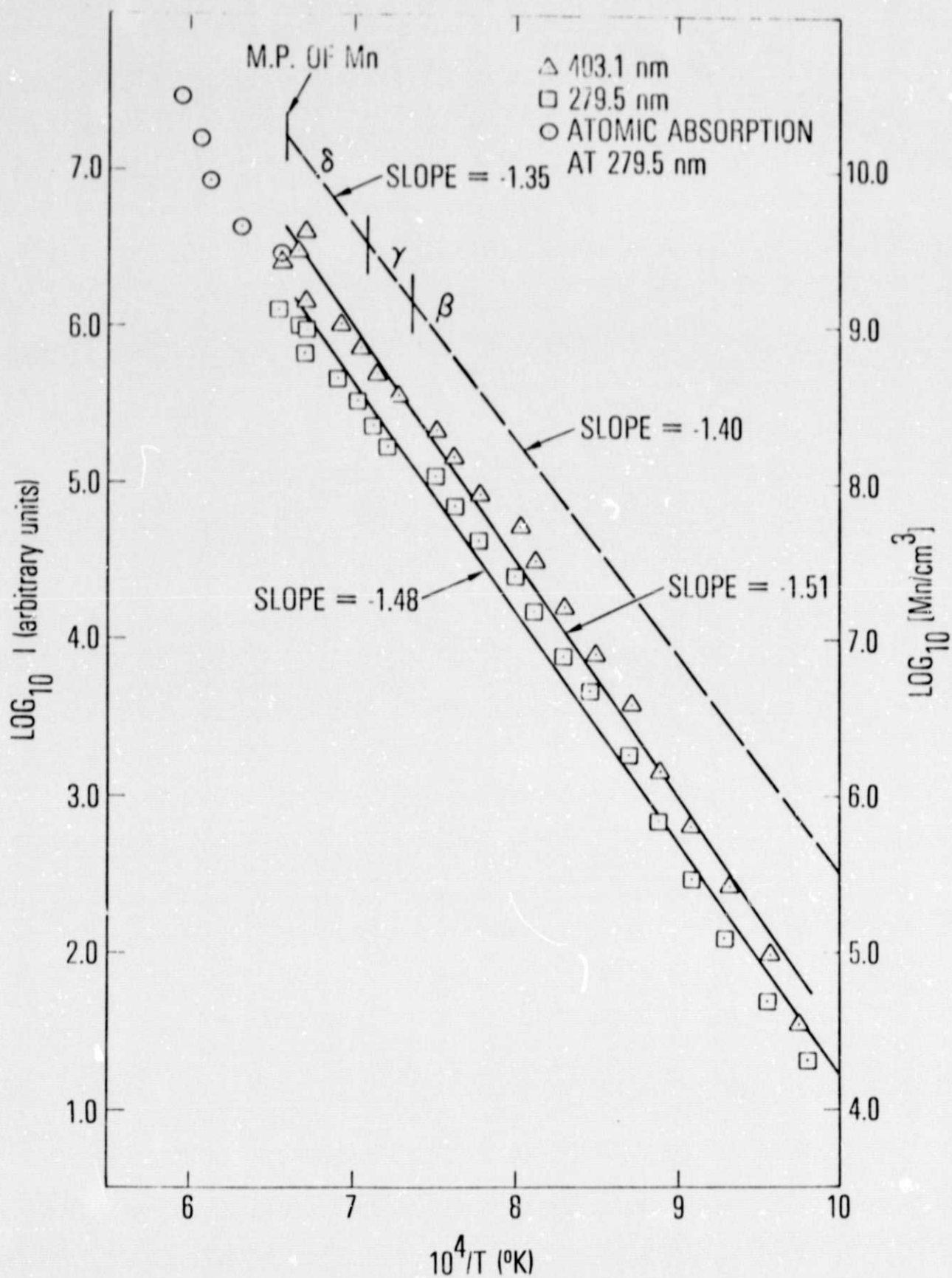


Figure 9: MTES Vapor Pressure Curve for Manganese

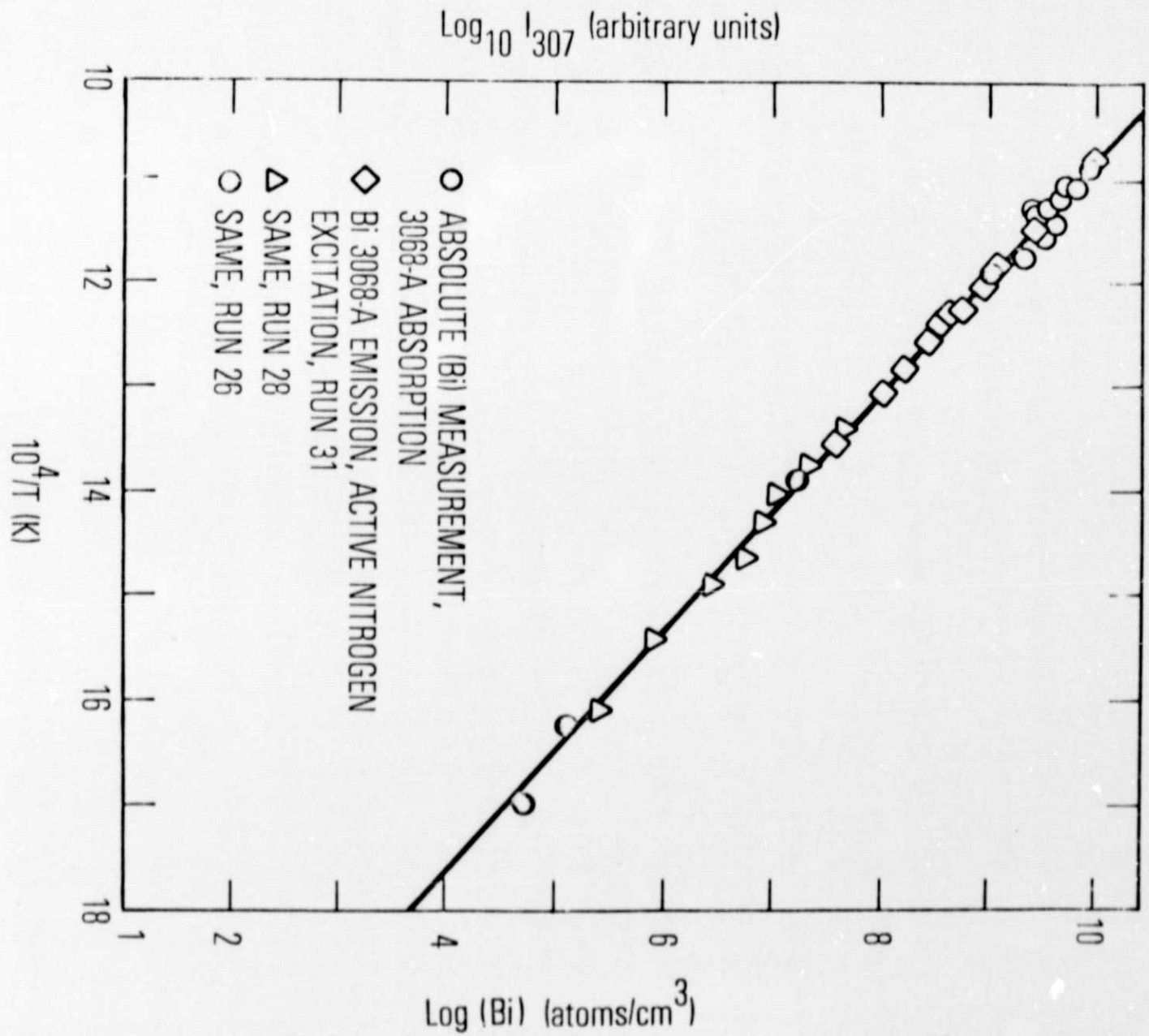


Figure 10: MTES Vapor Pressure Curve for Bismuth at 307 nm